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RESEARCH MEMORANDUM

VAPOR-FUEL-DISTRIBUTION EFFECTS ON COMBUSTION

PERFORMANCE OF A SINGLE TUBULAR COMBUSTOR

By Richard J. McCafferty

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Cleveland, Ohio

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RESEARCH MEMORANDUM

VAPOR-FUEL-DISTRIBUTION EFFECTS ON COMBUSTION

PERFORMANCE OF A SINGLE TUBULAR COMBUSTOR

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SUMMARY

An investigation was conducted using a single 4000-pound-thrust turbojet-engine combustor operating with liquid MIL-F-5616 and gaseous propane fuels to study the effects of hydrocarbon fuel distribution and fuel state on combustion performance. The MIL-F-5616 fuel was injected and atomized with the standard engine pressure-atomizing nozzle; data were available from a previous investigation for the same combustor operating with a different fuel nozzle and a similar (AN-F-32) fuel. The gaseous propane was distributed into the primary combustion zone with four fuel-injector designs. Altitude operational limits and attendant combustion efficiencies and effects of combustor inlet-air variables on combustion efficiency were determined.

Vapor-fuel distribution in the primary combustion zone was important because the altitude operational limits and efficiencies could be varied considerably by use of different fuel injectors that provided different fuel-air mixtures. Higher altitude operational limits and higher combustion efficiencies were obtained with vapor fuel than with liquid fuel atomized and distributed with the two designs of pressure-atomizing nozzle.

INTRODUCTION

Research is being conducted at the NACA Lewis laboratory to obtain information on the relative importance of various factors affecting the altitude performance of aircraft turbine engine combustors. Part of this research is aimed to provide information on the combustion characteristics of liquid and vapor hydrocarbon fuels and particularly to show whether vapor fuels have inherently better characteristics than liquid fuels when injected into a combustor operating at altitudes where the inlet-air conditions are adverse to combustion.

Previous reports (references 1 and 2) show that liquid-fuel combustion is unfavorably affected by increasing altitude; that is, as the altitude increases, the combustion efficiency begins dropping at an accelerating rate, the combustion instability increases, and finally complete flame extinction occurs. This altitude effect is in part attributed to the lack of rapid attainment of proper fuel-air mixtures in the primary combustion zone at high-altitude conditions. In these combustors the liquid fuel was atomized, vaporized, and mixed with air before combustion occurred. Quenching by dilution air limited the residence time available for complete combustion.

Because vapor fuel has higher diffusion coefficients and the time required for the vaporization process is eliminated, vapor fuel should provide a combustible fuel-air mixture in the primary combustion zone more rapidly than liquid fuel and, consequently, should provide higher efficiency at low inlet-air pressures and temperatures. The effect of fuel-air distribution with both liquid and vapor fuels must be evaluated before accurate conclusions can be formed regarding the importance of fuel state.

The effect of fuel-air distribution on combustion characteristics with only vapor fuel is presented herein. A comparison is made of the vapor-fuel performance with the liquid-fuel performance using two designs of pressure-atomizing nozzle; systematic variation of the liquid-fuel distribution was not made in the investigations reported herein. The data were obtained by operation of a single combustor with liquid MIL-F-5616 and gaseous propane fuels. Variation in distribution of the vapor fuel in the primary combustion zone was accomplished by the use of four fuel-injector designs. The combustion characteristics were evaluated by determining the altitude operational limits and attendant combustion efficiencies and effects of inlet-air pressure, temperature, and velocity on combustion efficiency at standard conditions of 620° R and 15 pounds per square inch absolute. Information on the carbon-forming tendencies, ignition characteristics, and combustor-outlet temperature distributions obtained with the liquid and vapor fuels is also included.

APPARATUS AND INSTRUMENTATION

Equipment

The investigations were conducted in a single combustor from a J35-C-3 turbojet engine. The combustor was connected to the laboratory air supply, as diagrammatically shown in figure 1; air quantity and pressure were regulated by remote-control valves upstream and downstream

of the combustor. The desired inlet-air temperature was obtained by burning a portion of the air with gasoline in a preheater and then mixing uniformly with the rest of the air upstream of the combustor. The effect on the constituents of the inlet air due to the added products of combustion is discussed in reference 2. The exhaust gases were cooled by water sprays in the exhaust ducting.

The combustor-inlet section and the combustor itself were furnished by the manufacturer. The inlet and outlet ducts were fabricated to simulate the dimensions and contours of corresponding engine ducts. The combustor outer wall was reinforced with metal bands to eliminate structural failure at the low interior pressures investigated. Observation windows were located axially along the combustor to permit visual observation of combustion.

Instrumentation

The number and location of instruments at the instrumentation planes shown in figure 1 are as follows:

Type of instrument	Number of instruments			
	Instrumentation plane			
	2	3	4	5
One-thermocouple rake	2			3
Three-tube total-pressure rake	3			
Five-thermocouple rake		7		
Five-tube total-pressure rake			7	
Static-pressure orifice	1	1	1	

All temperature and total-pressure measurements were taken at the center of equal areas. Locations of the points of measurement at the respective instrumentation planes are shown in figure 2 and the instrumentation details are shown in figure 3. Air-flow rate was metered by a square-edge orifice installed according to A.S.M.E. specifications; temperatures were indicated by self-balancing potentiometers; and liquid-fuel-flow rate was indicated by a calibrated rotameter. The gaseous propane, which was supplied from the laboratory fuel system, was measured by a calibrated orifice and the readings were checked by a rotameter. All calculations of propane weight flow from flowmeter readings were based on propane density values from reference 3 to eliminate errors due to deviation from the perfect-gas law.

Fuel Injectors

The MIL-F-5616 liquid fuel was injected through a duplex-type pressure-atomizing nozzle and flow divider apparatus that is standard for the J35-C-3 engine. Data are available in reference 4 for operation with liquid fuel and a different nozzle. The different gaseous-propane injectors that were installed in the combustor in the same relative position as the liquid-fuel nozzle are:

Single-port injectors. - A standard duplex-type nozzle was altered as shown in figure 4(a) to provide for the injection of the gaseous propane through a single port at the center line of the combustor. The desired 0.20- or 0.60-inch-port-diameter disk was welded to the end of the main nozzle body.

Multiport injector. - The standard duplex-type nozzle was modified by removing the internal parts and replacing the end of the nozzle with a 1/2-inch standard-pipe coupling machined to the same outer diameter as the nozzle. A 1/2-inch-pipe nipple was attached on which eight 1/4-inch-diameter tubes were arranged as radial spokes. Five 1/32-inch-diameter holes were drilled at the center of equal areas in each tube. A diagrammatic sketch of this injector is shown in figure 4(b).

Tube injector. - A stainless-steel 3/4-inch-diameter tube was drilled with 1/32-inch-diameter holes to provide the same port area as the multiport injector, and the holes were spaced circumferentially at predetermined lengths from the upstream end of the tube to maintain the same proportion of total-fuel-port area to total-liner primary-hole area. The primary-zone-hole area was considered to be one-fourth of the total-hole area of the liner. A diagrammatic sketch of this injector is shown in figure 4(c).

PROCEDURE

The combustion performance was studied by (1) determining altitude operational limits and combustion efficiencies at various simulated flight conditions, and (2) determining the influence of combustor-inlet pressure, temperature, and velocity on combustion efficiency and temperature rise at the standard conditions of 620° R and 15 pounds per square inch absolute. These determinations were made for each of the following fuels and fuel-injection systems: MIL-F-5616 with the standard duplex nozzle; and propane with the 0.20-inch single-port injector, the 0.60-inch single-port injector, the multiport injector, and the tube injector.

Estimated combustor-inlet-air conditions and combustor-outlet-gas temperatures corresponding to zero-ram operation of the engine at various altitudes and rotor speeds were obtained from reference 5. These data were used to establish the combustor operating conditions necessary to simulate engine operation at any desired altitude and rotor speed. Details of the operational methods and data recording procedures are described in reference 2. Bracketing the altitude operational limits at some rotor speeds was impossible because of the exhaust facility limitations; these altitude operational limits were then estimated by extrapolation of values of temperature rise attainable and combustion efficiencies at altitudes below the operational limit.

With the use of charts in reference 6, the combustion efficiency was computed as the ratio of the measured enthalpy rise across the combustor to the heating value of the fuel. Air reference velocity values quoted herein were computed from the maximum cross-sectional area of the combustor flow passage, the inlet-air density, and the total-air-flow rate. The thermocouple indications were taken as true values of total temperatures with no corrections for radiation or stagnation effects.

RESULTS AND DISCUSSIONS

Altitude operational limits of the single tubular combustor are presented in figures 5 and 6 for each fuel and fuel injector investigated. The combustion efficiencies obtained at each simulated-altitude - rotor-speed condition are also indicated. The curve in each figure separates the region of sufficient and insufficient combustor-outlet temperatures attainable for nonaccelerating operation of the engine. A comparison of the altitude operational limits obtained is shown in figure 7. The combustion efficiencies obtained at two constant rotor speeds in the region of the altitude operational limits are compared in figure 8.

Vapor-Fuel Distribution

Effect of single propane jet. - Comparison of results obtained with 0.20- and 0.60-inch-diameter jets of propane fuel show that the large-diameter low-velocity jet provided altitude operational limits 20,000 feet higher than the small-diameter high-velocity jet (fig. 7). The large-diameter jet is believed to provide a more uniform fuel-air distribution in the primary zone and a more stable combustion zone at high altitudes because of additional fuel dispersion and breaking up

caused by the turbulence of the incoming primary air. The small-diameter jet, having a higher velocity flow at the same mass flow, was not as rapidly dispersed and consequently did not provide enough mixing of fuel and air in the low-velocity region of the primary zone.

Effect of axial- and radial-plane fuel distribution. - The radial fuel distribution provided by the multiport injector gave higher altitude operational limits (fig. 7) and combustion efficiencies (fig. 8) than the distribution provided by the single-port jets at high rotor speeds. The low-velocity large-diameter jet, however, gave operational limits approximately 8000 feet higher at low rotor speeds. The axially distributed fuel (tube injector) provided higher operational limits and similar combustion efficiency values as the other types of fuel distribution studied (figs. 7 and 8). This result indicates that best combustion performance is obtained at high altitude conditions if the vapor-fuel distribution is matched to the air distribution along the length of the combustion zone.

Liquid-Fuel Distribution

The effect of liquid-fuel atomization with its attendant fuel-distribution effects is also shown in figure 7 by comparison of the operational limits obtained with MIL-F-5616 (formerly specification AN-F-32) fuel in this investigation and those obtained with AN-F-32 in reference 4. The more advanced design of fuel nozzle provided finer fuel atomization and gave higher operational limits than those obtained with the earlier fuel nozzle. Further improvements in fuel-injection systems may provide additional performance gains with liquid fuels.

Fuel State

The results presented in figures 7 and 8 show that higher altitude operational limits and combustion efficiencies can be obtained with vapor fuel than with liquid fuel atomized and distributed with the two types of pressure-atomizing nozzle. Fuel distribution, however, has a large effect on performance with both types of fuel and if the liquid-fuel distribution and atomization were optimized, the differences in performance due to fuel state might not be as great as indicated by the curves of figures 7 and 8.

Combustor Inlet-Air Variables

Variation of combustion efficiency with inlet-air pressure, temperature, and reference velocity is shown in figures 9, 10, and 11, respectively. The original data were taken at a series of fuel-air ratios for each inlet parameter value studied and these curves were cross-plotted at 650° and 1200° F combustor temperature rise from those data. In figures 9 and 10, curves with combustion efficiency values over 100 percent are due to $\pm 1\frac{1}{2}$ percent accuracy of the data. The combustion efficiencies with both liquid and vapor fuels decreased with decreasing pressure and temperature and increasing velocity. This trend has already been established with liquid fuels in previous investigations (references 1 and 2). The efficiencies obtained with the vapor fuel, exclusive of the small-diameter-jet distribution, were less affected by changes in inlet pressure and temperature than those obtained with the liquid fuel, which indicates that temperature and pressure effects on rates of vaporization were affecting combustion performance. The effects on the small-diameter vapor injector are probably due to fuel-distribution phenomena. When the velocity was varied (fig. 11), little difference was noted among the two fuels and various fuel-injection systems; all combinations provided lower efficiencies at high velocities.

Temperature Distribution at Combustor Outlet

An attempt was made to correlate the combustor-outlet temperature distribution for each of the fuels and fuel injectors investigated. The results are shown in figure 12 where the mean deviation of individual outlet temperature indications from the average outlet temperature is plotted against temperature rise through the combustor. The data points shown were chosen at random as a representative sample of the data obtained during the investigations. The curves indicate that liquid MIL-F-5616 fuel provided a more uniform combustor-outlet temperature than gaseous propane fuel regardless of the injector design.

Miscellaneous Observations

Observations were made during the investigation regarding the behavior of the two fuels. The color of the flames produced by the combustion of both MIL-F-5616 and propane was predominantly yellow at the higher pressures and changed to blue as the pressure was decreased. The small-diameter propane jet produced rather violent combustion pulsations at all fuel-air ratios and was very sensitive to fuel-flow changes at high fuel-air ratios with blow-outs frequently occurring.

Although no systematic study was made of the ignition characteristics of the fuels and fuel-injection systems investigated, standard spark-plug ignition was much easier with gaseous propane than with the liquid fuel. Ignition was accomplished with propane fuel at conditions simulating high-altitude operation, 8 to 10 inches mercury absolute being an approximate low-pressure limit for propane ignition, whereas at this pressure the MIL-F-5616 fuel injected with the standard nozzle could not be ignited.

Carbon deposits produced by propane were negligible except with the multiport injector. Figure 13 shows two types of carbon deposit formed on the tubes of the injector during the investigation: (1) hard, scale-like films having a tendency to break up in flakes, and (2) soft, loose grainy structures that piled up in clumps. No appreciable deposits were noticed on the liner walls but some carbonaceous material accumulated in the liner dome.

SUMMARY OF RESULTS

The results obtained in the investigation of the effect of fuel state and vapor-fuel distribution on combustion performance in single tubular combustor from a 4000-pound-thrust turbojet engine are summarized as follows:

1. Distribution of the vapor fuel within the primary zone of the combustor markedly affected performance. The optimum distribution investigated was the gradual axial admission of fuel along the center line of the combustion zone.

2. Higher altitude operational limits and combustion efficiencies were obtained with gaseous propane fuel and the better injectors than with atomized MIL-F-5616 liquid fuel injected by two designs of pressure-atomizing nozzle.

3. Independently decreasing combustor-inlet pressure and temperature and increasing reference velocity lowered the combustion efficiency for both liquid and vapor fuels. The efficiencies obtained with the vapor fuel, exclusive of the small-diameter single-port injector, were less detrimentally affected by changes in inlet pressure and temperature than those obtained with the liquid fuel.

4. Ignition was accomplished at lower pressures with vapor fuel than with the liquid fuel.

5. Combustor-outlet temperatures were more uniform with liquid fuel than with vapor fuel.

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Cleveland, Ohio.

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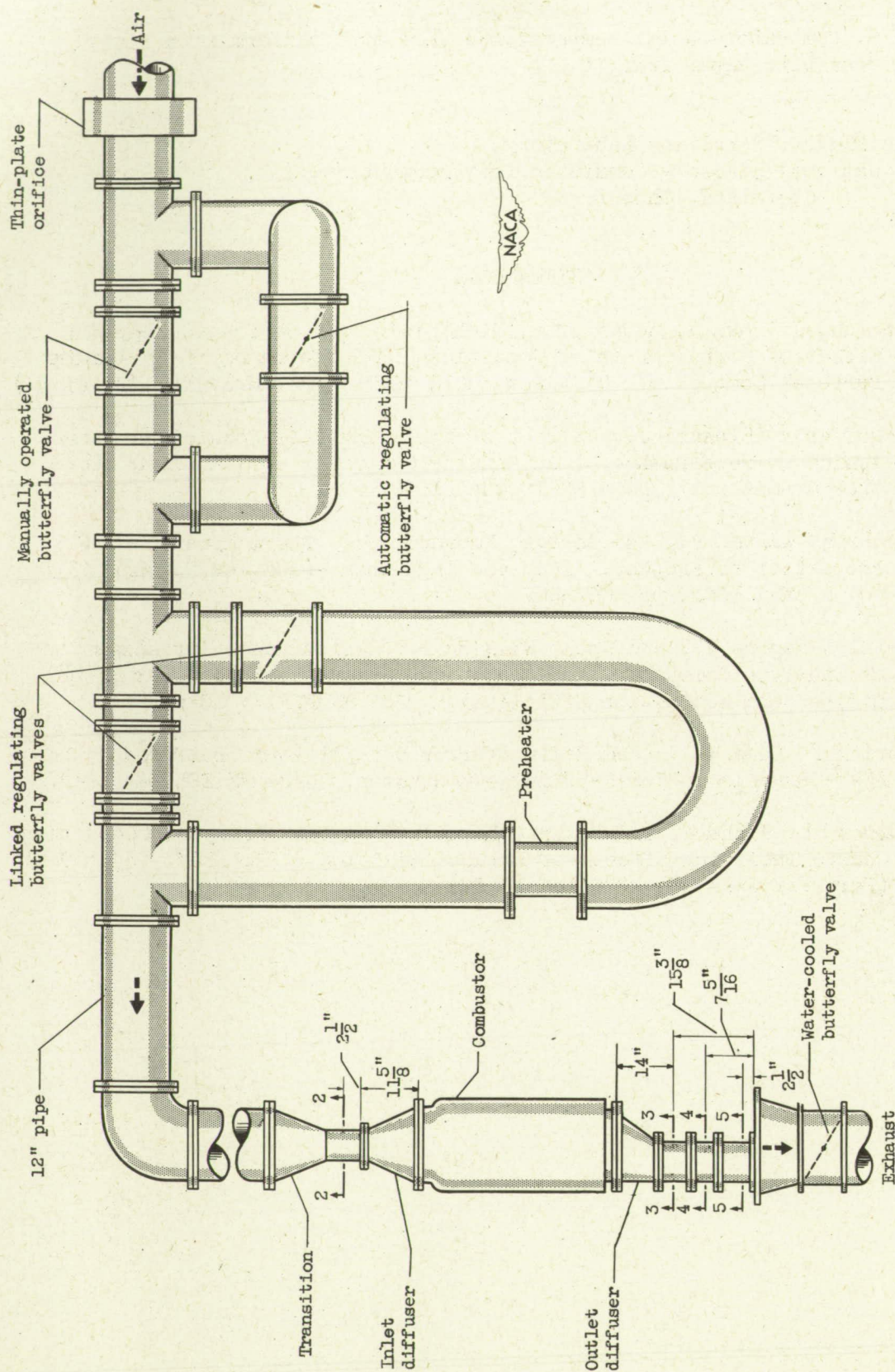


Figure 1. - Diagrammatic sketch of single combustor setup.

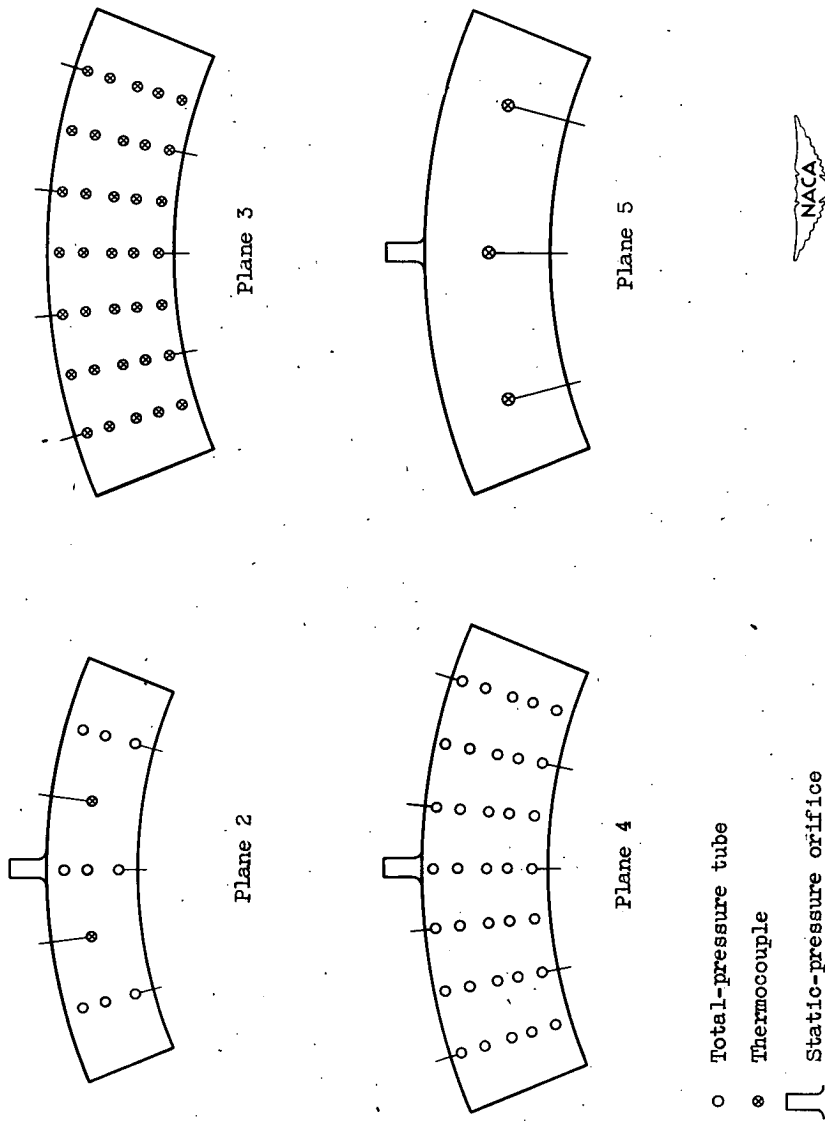
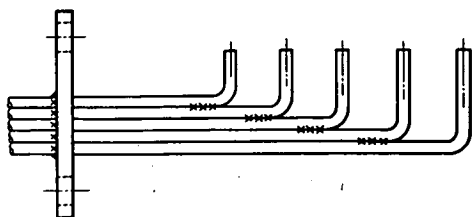
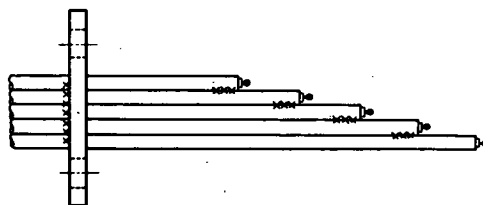


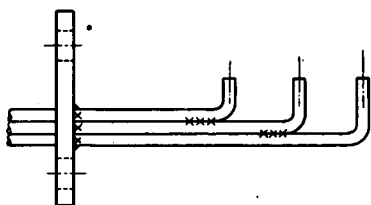
Figure 2. - Stations of measurement at the instrumentation planes shown in figure 1.



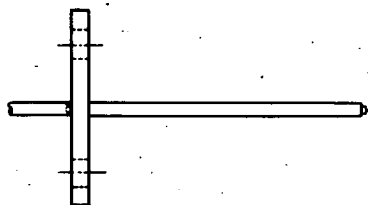
Five-tube total-pressure rake



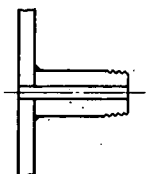
Five-thermocouple rake



Three-tube total-pressure rake



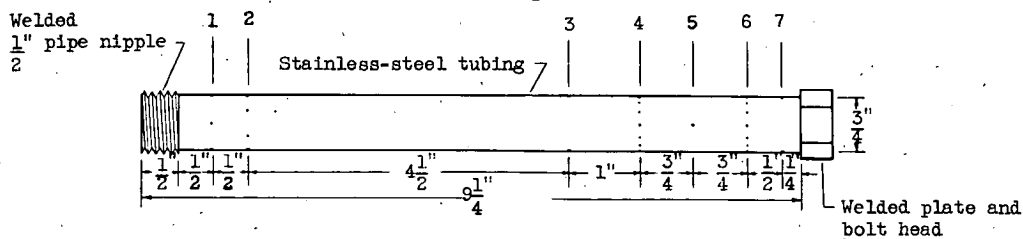
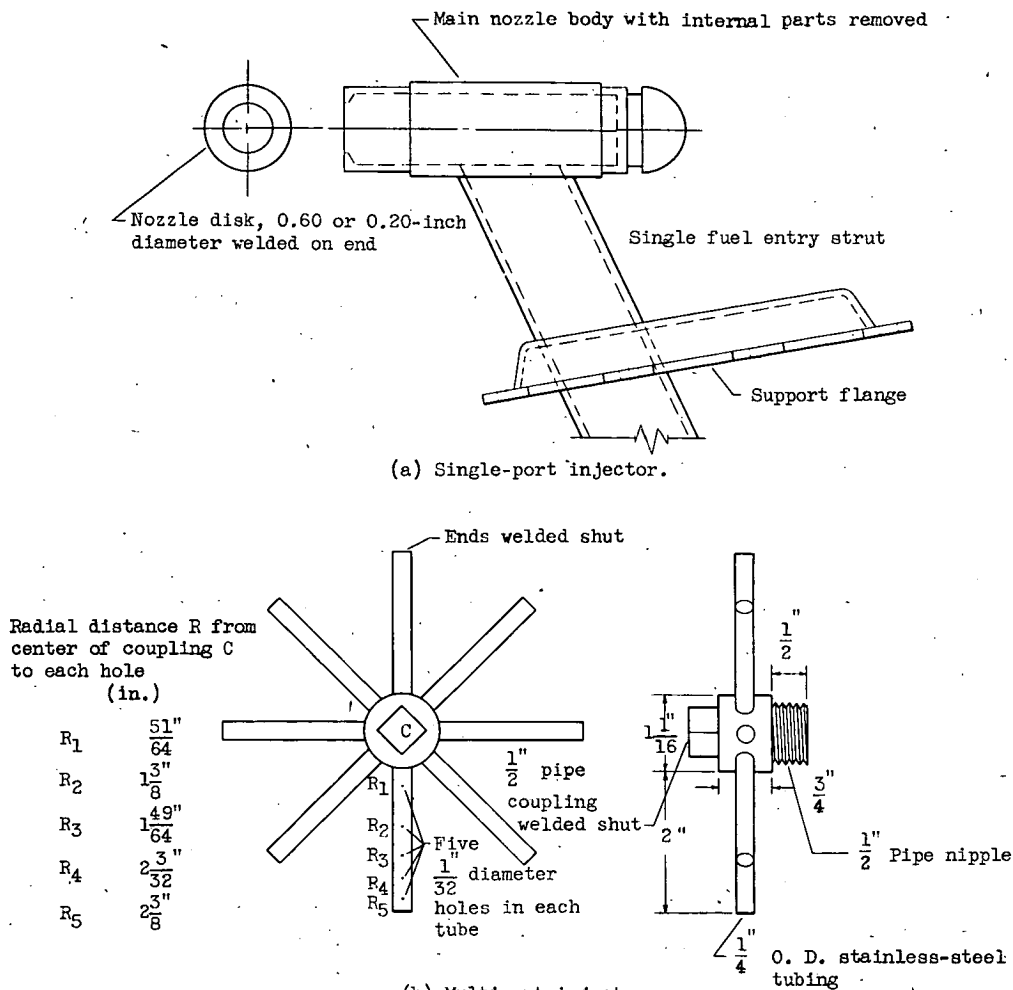
One-thermocouple rake



Static-pressure orifice connection



Figure 3. - Instrumentation details.



Station	Number of 1/32-inch- diameter holes	Spacing (deg)
1	4	90
2	6	60
3	2	180
4	12	30
5	2	180
6	12	30
7	2	180

(c) Tube injector.

Figure 4. - Diagrammatic sketch of several gaseous-propane injectors.

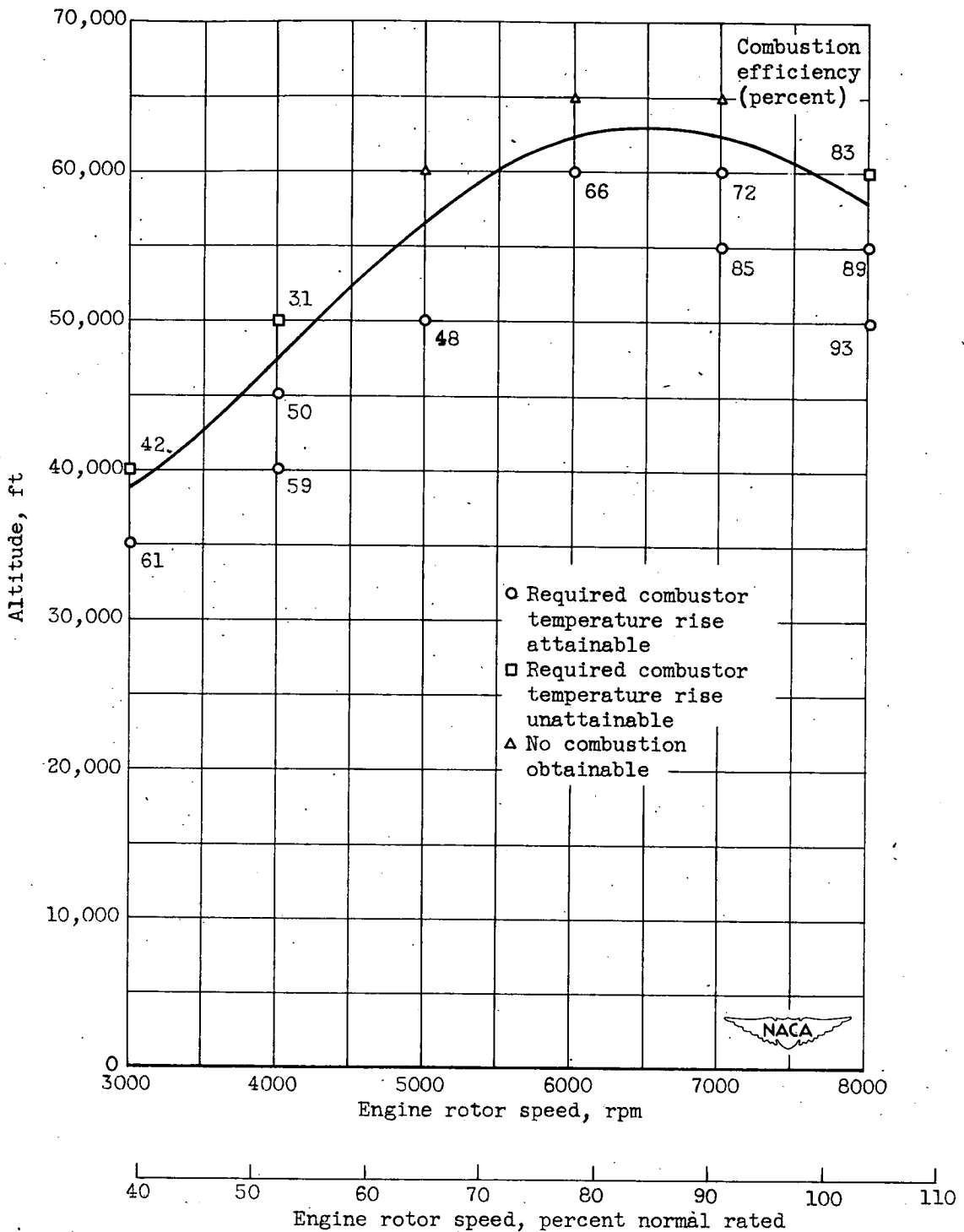
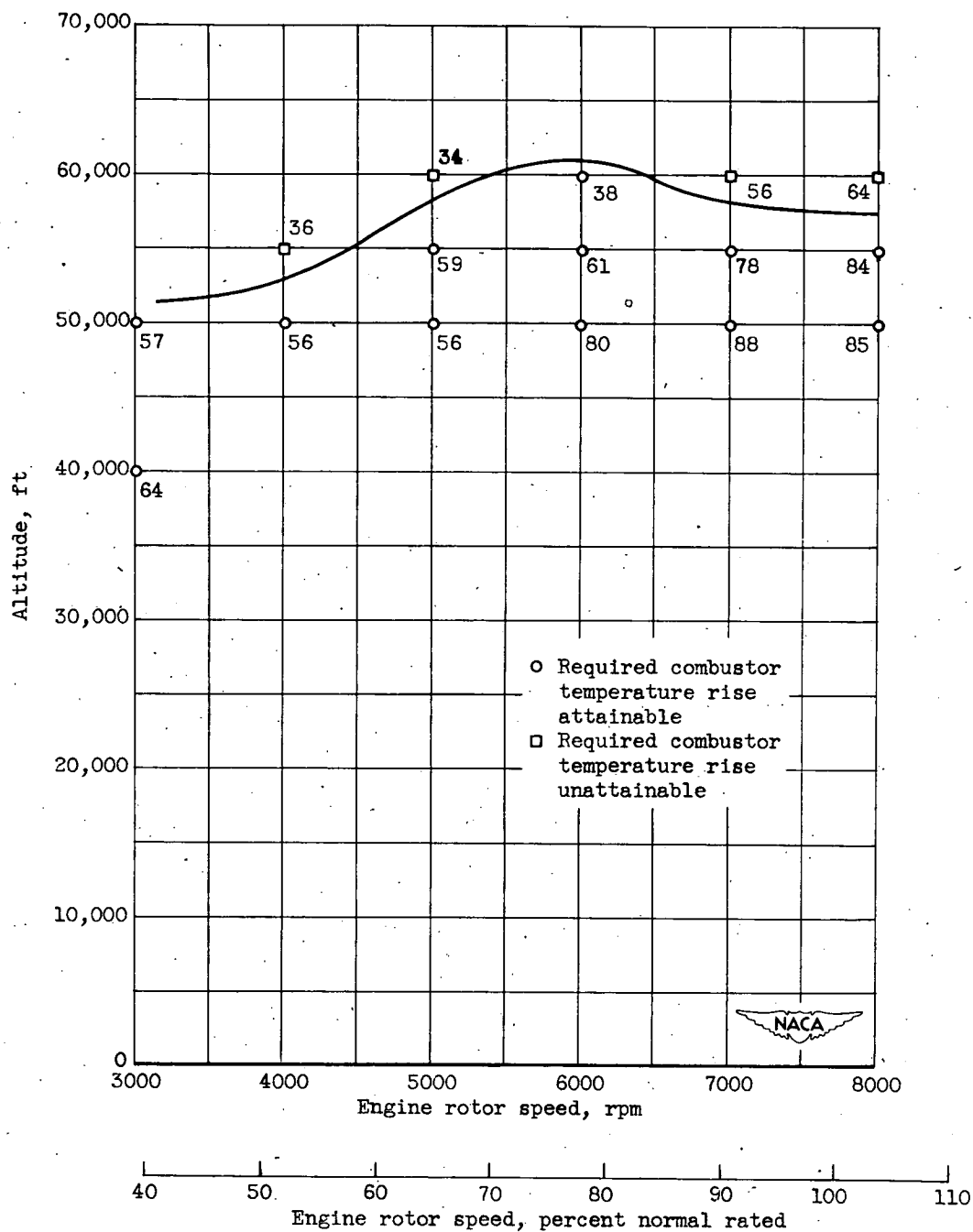
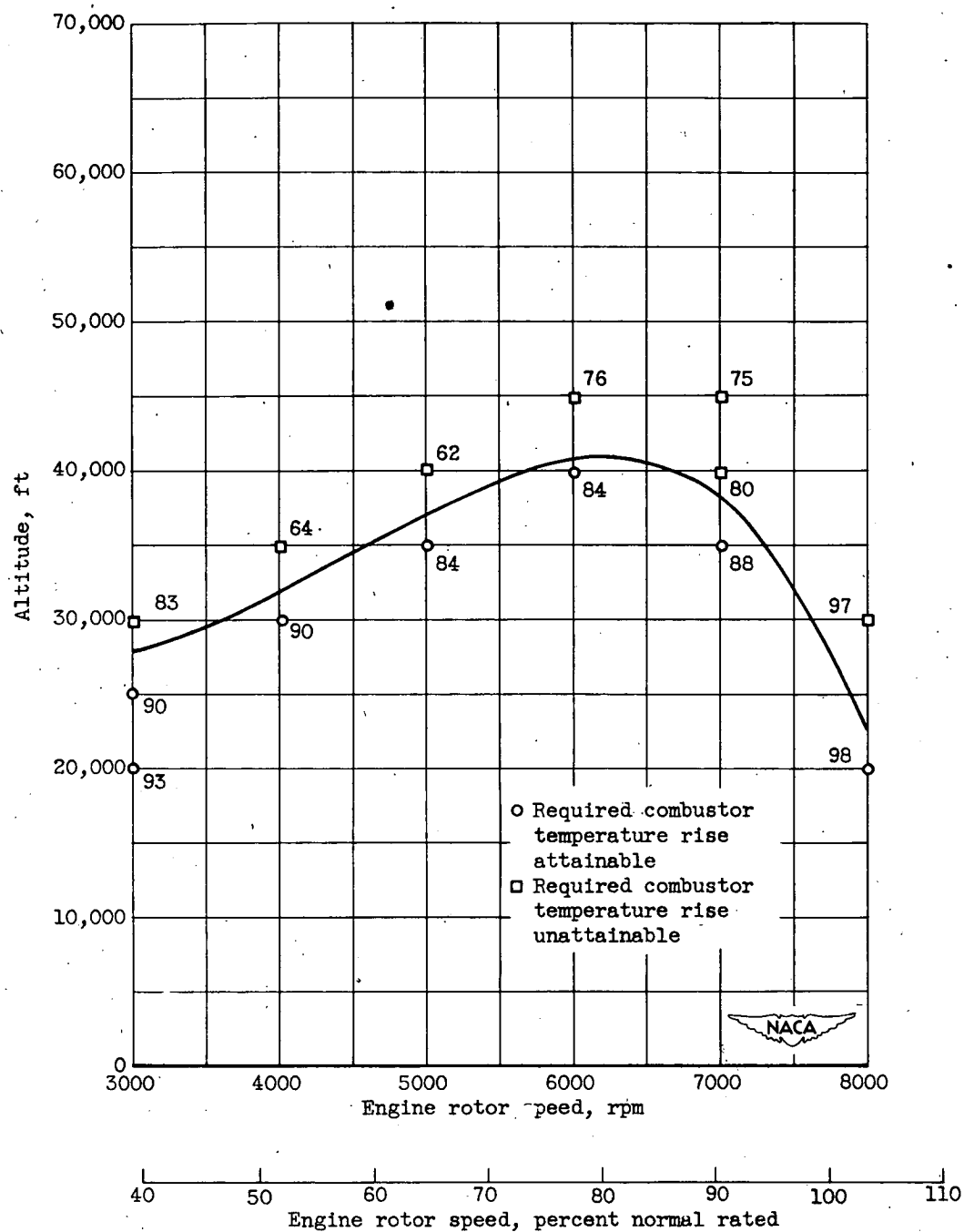


Figure 5. - Altitude operational limits and combustion efficiencies of single tubular combustor operating with liquid MIL-F-5616 fuel and standard fuel nozzle. Simulated flight Mach number, 0.



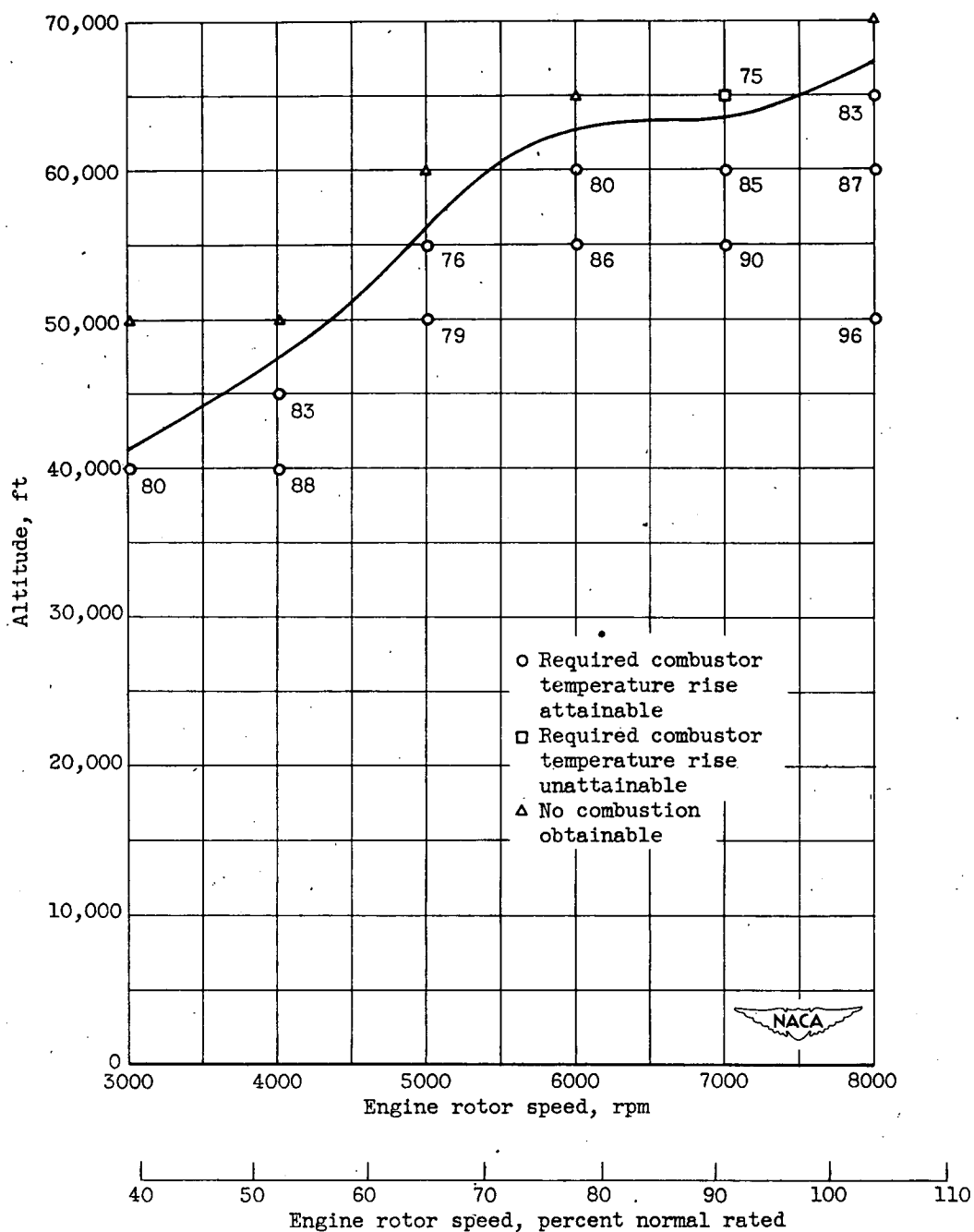
(a) 0.60-inch-diameter single-port injector.

Figure 6. - Altitude operational limits and combustion efficiencies of single tubular combustor operating with gaseous-propane fuel injected with four fuel-injector designs. Simulated flight Mach number, 0.



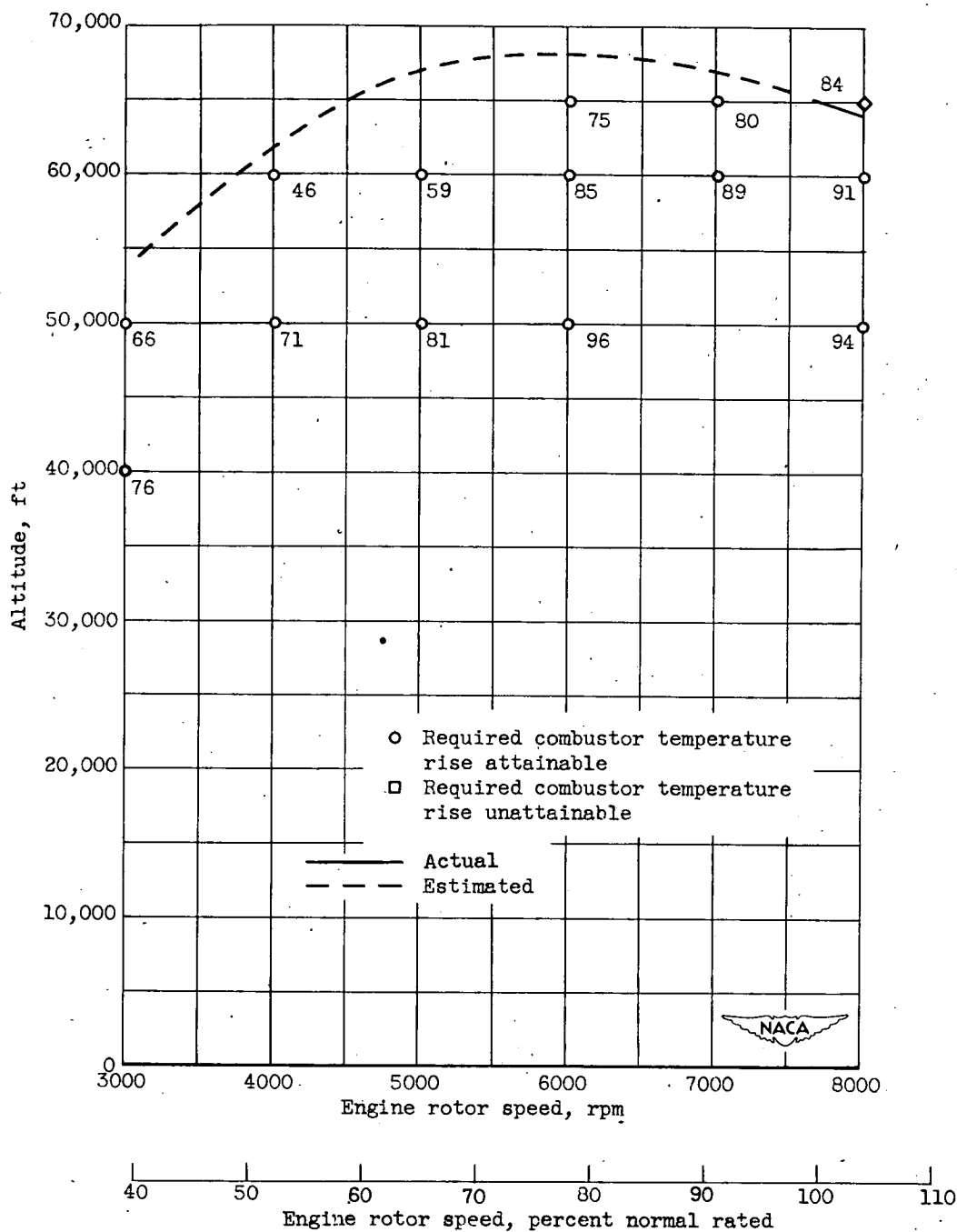
(b) 0.20-inch-diameter single-port injector.

Figure 6. - Continued. Altitude operational limits and combustion efficiencies of single tubular combustor operating with gaseous-propane fuel injected with four fuel-injector designs. Simulated flight Mach number, 0.



(c) Multiport injector.

Figure 6. - Continued. Altitude operational limits and combustion efficiencies of single tubular combustor operating with gaseous-propane fuel injected with four fuel-injector designs. Simulated flight Mach number, 0.



(d) Tube injector.

Figure 6. - Concluded. Altitude operational limits and combustion efficiencies of single tubular combustor operating with gaseous-propane fuel injected with four fuel-injector designs. Simulated flight Mach number, 0.

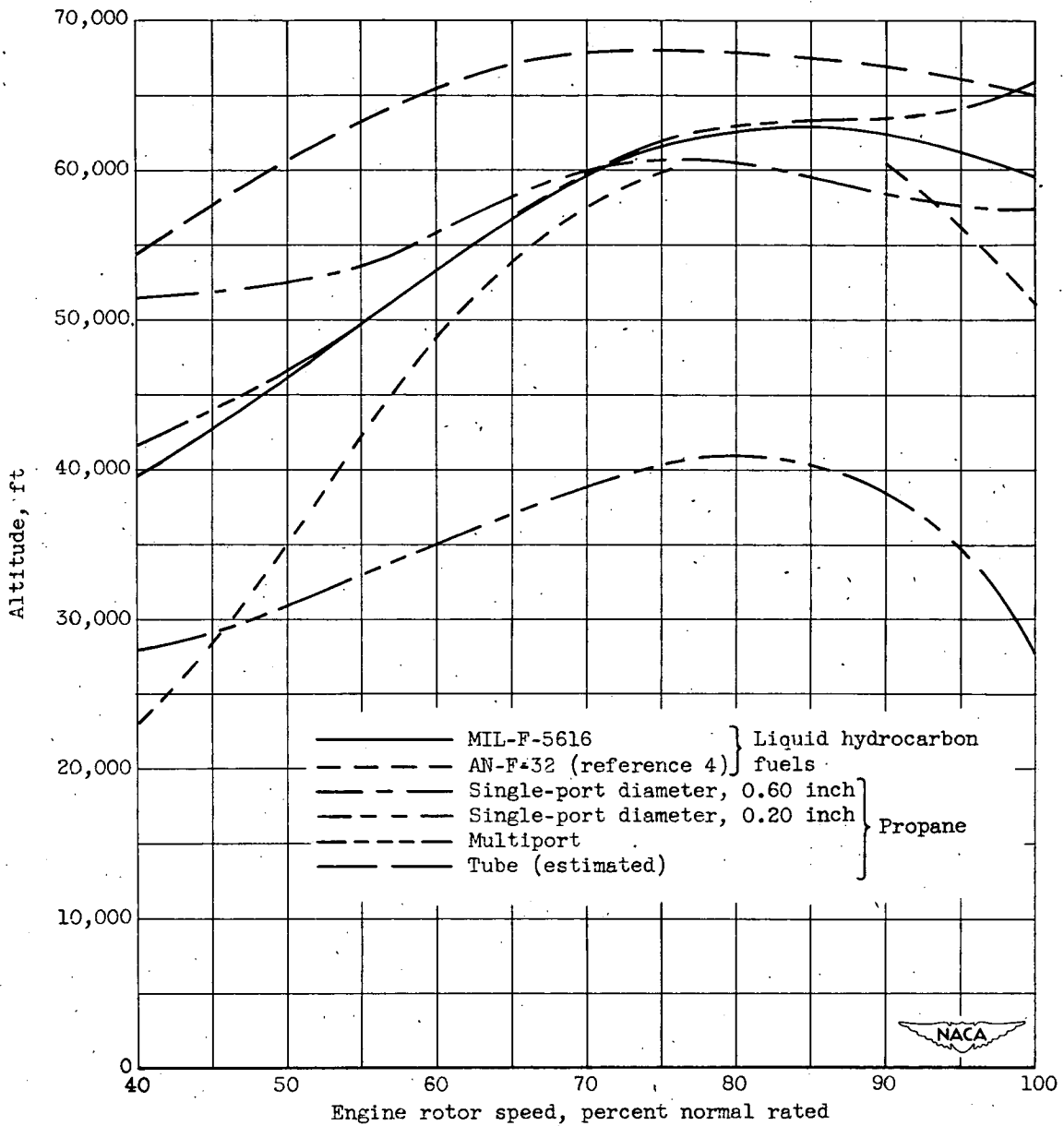


Figure 7. - Comparison of altitude operational limits of single tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods. Simulated flight Mach number, 0.

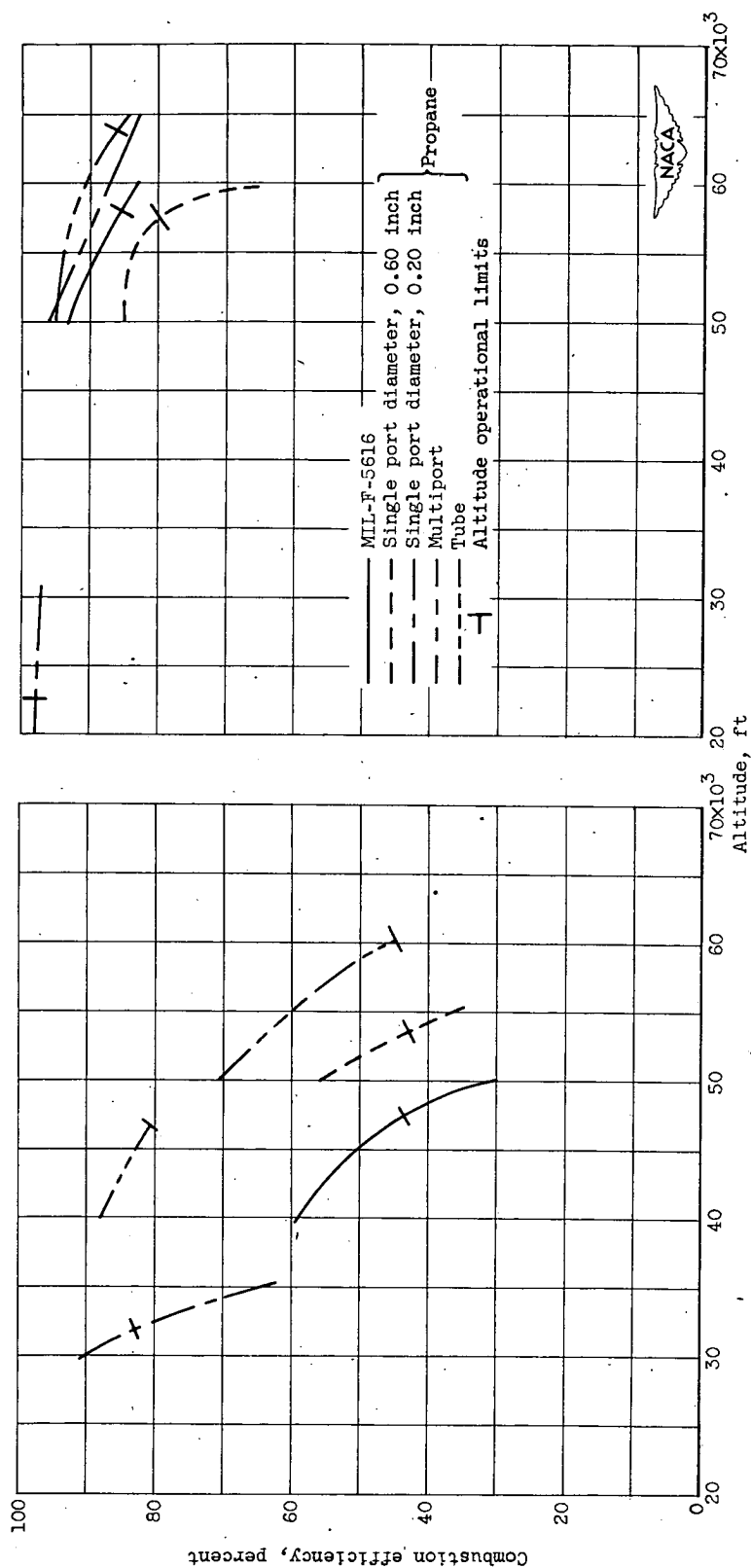
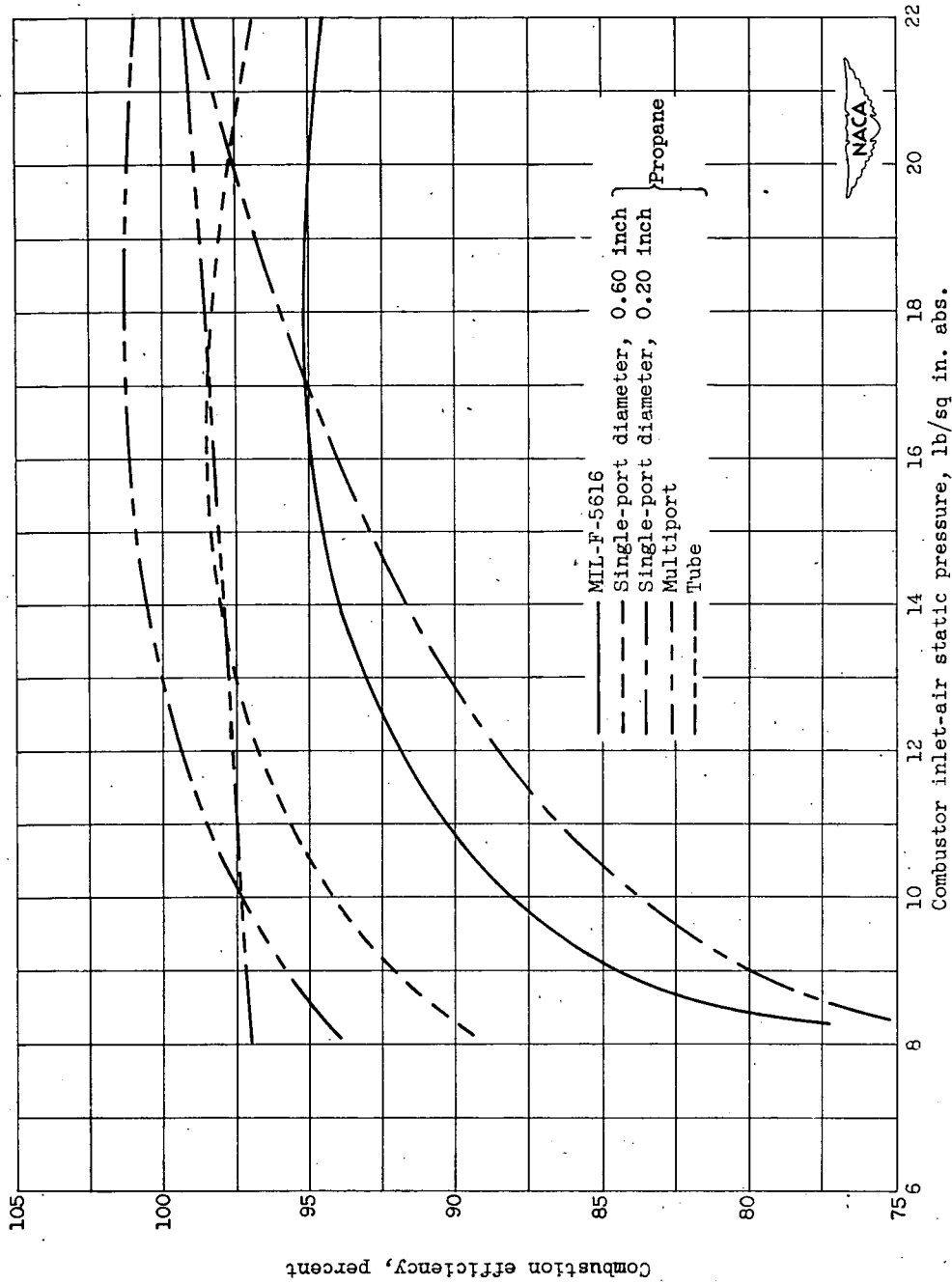
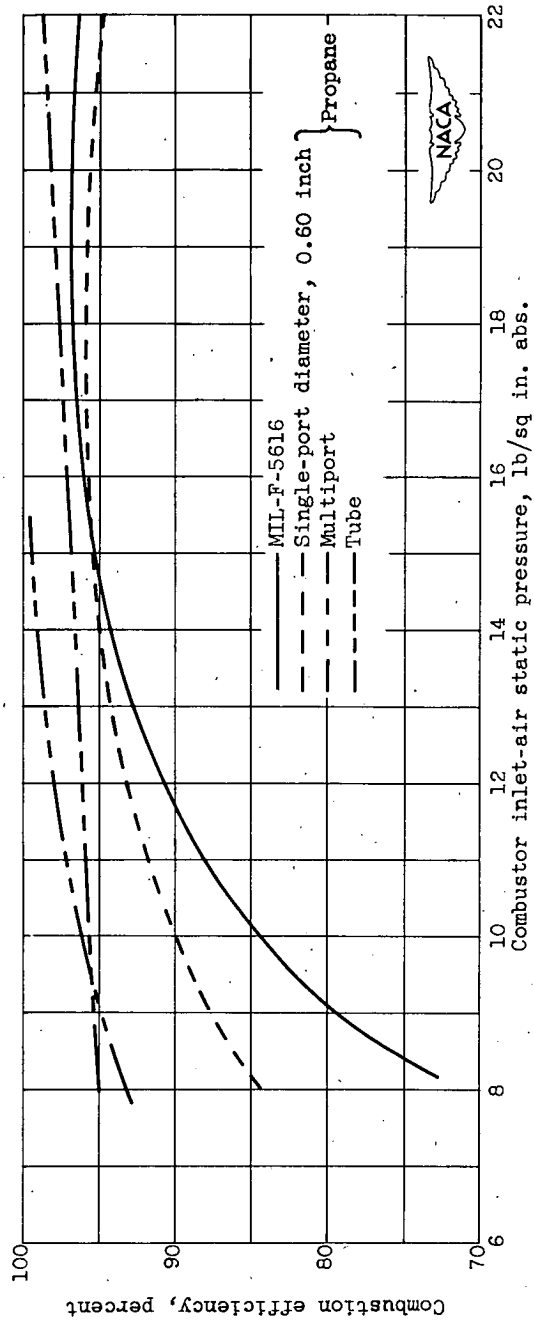


Figure 8. - Variation of combustion efficiency with altitude of single tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods.



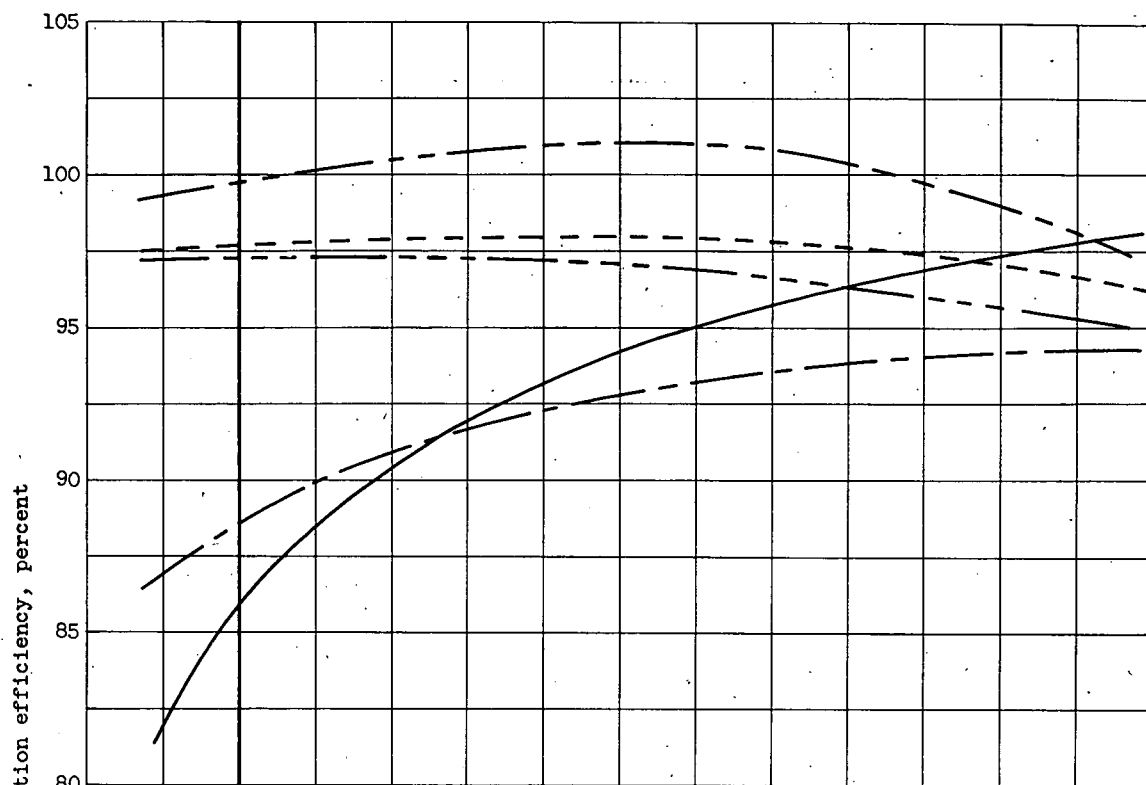
(a) Temperature rise, 650° F.

Figure 9. - Variation of combustion efficiency with inlet-air static pressure of tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods. Combustor conditions: temperature, 160° F; velocity, 80 feet per second.

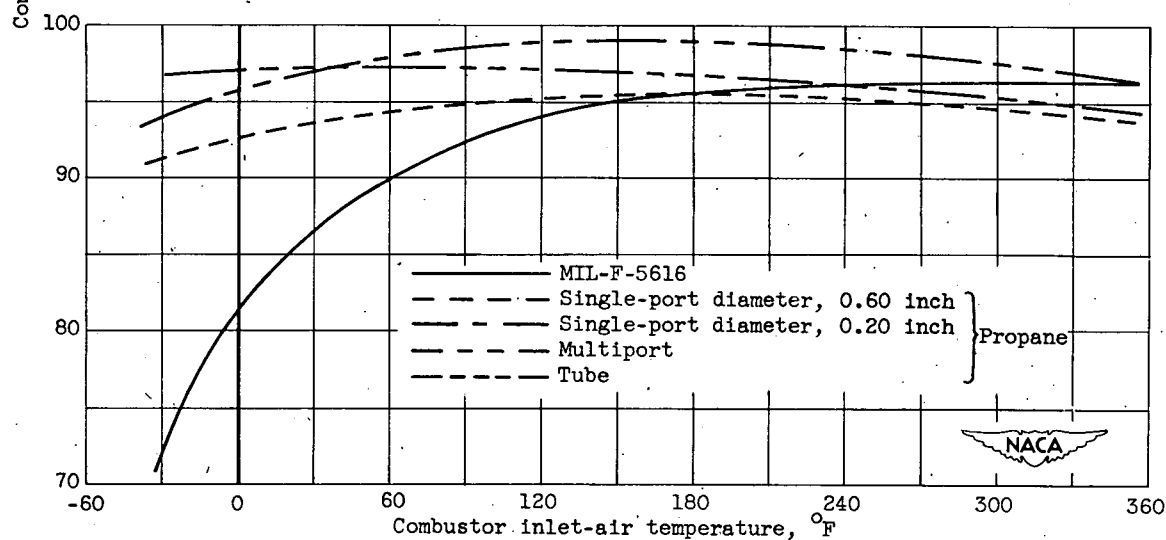


(b) Temperature rise, 1200° F.

Figure 9. - Concluded. Variation of combustion efficiency with inlet-air static pressure of tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods. Combustor conditions: temperature, 160° F; velocity, 80 feet per second.

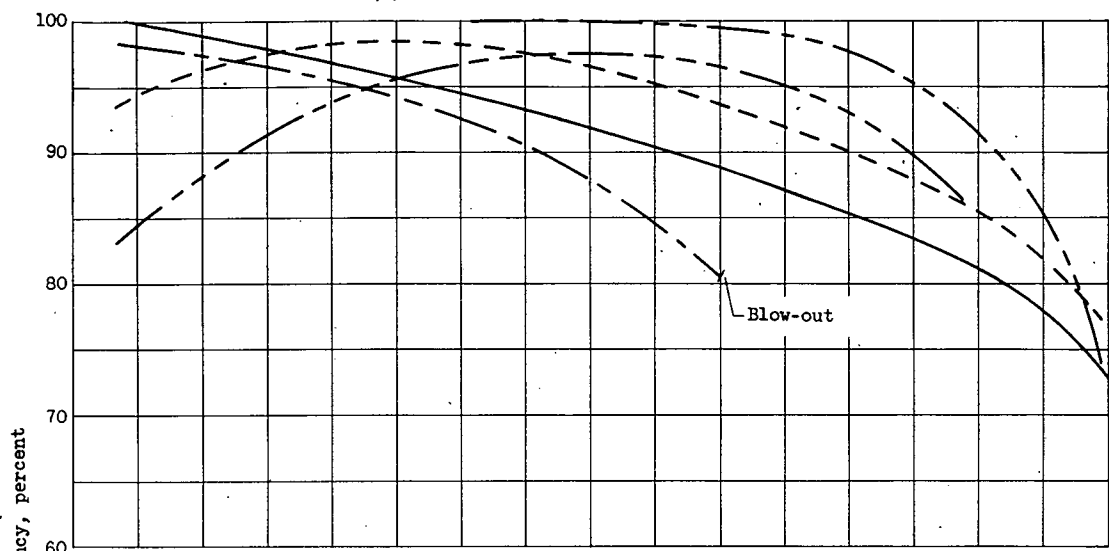


(a) Temperature rise, 650° F.

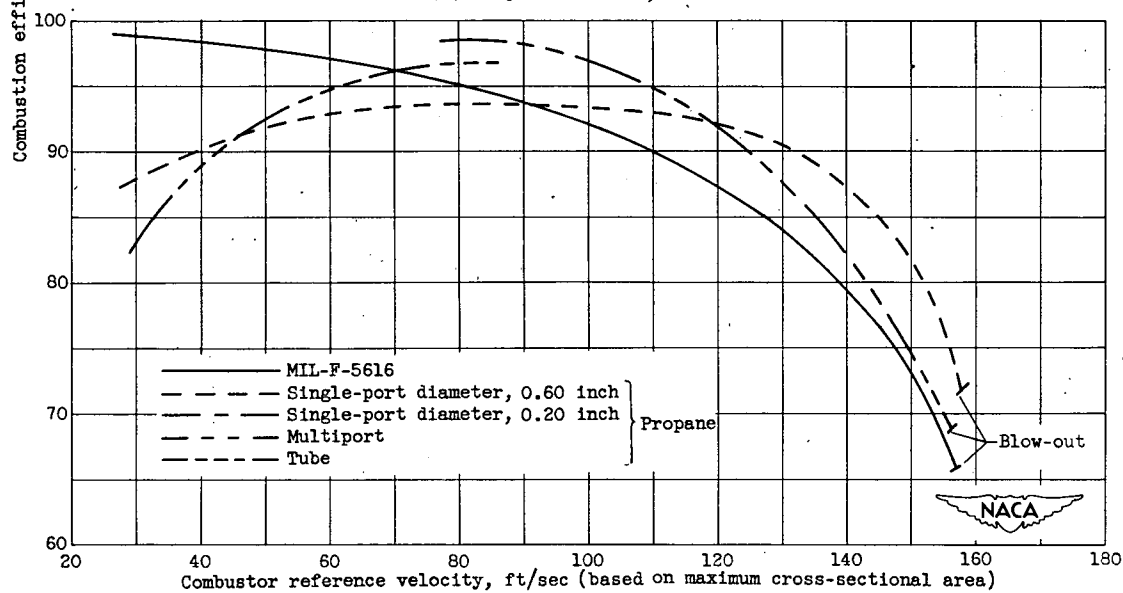


(b) Temperature rise, 1200° F.

Figure 10. - Variation of combustion efficiency with inlet-air temperature of tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods. Combustor conditions: pressure, 15 pounds per square inch absolute; velocity, 80 feet per second.



(a) Temperature rise, 650° F.



(b) Temperature rise, 1200° F.

Figure 11. - Variation of combustion efficiency with reference velocity of tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods. Combustor conditions: temperature, 160° F; pressure, 15 pounds per square inch absolute.

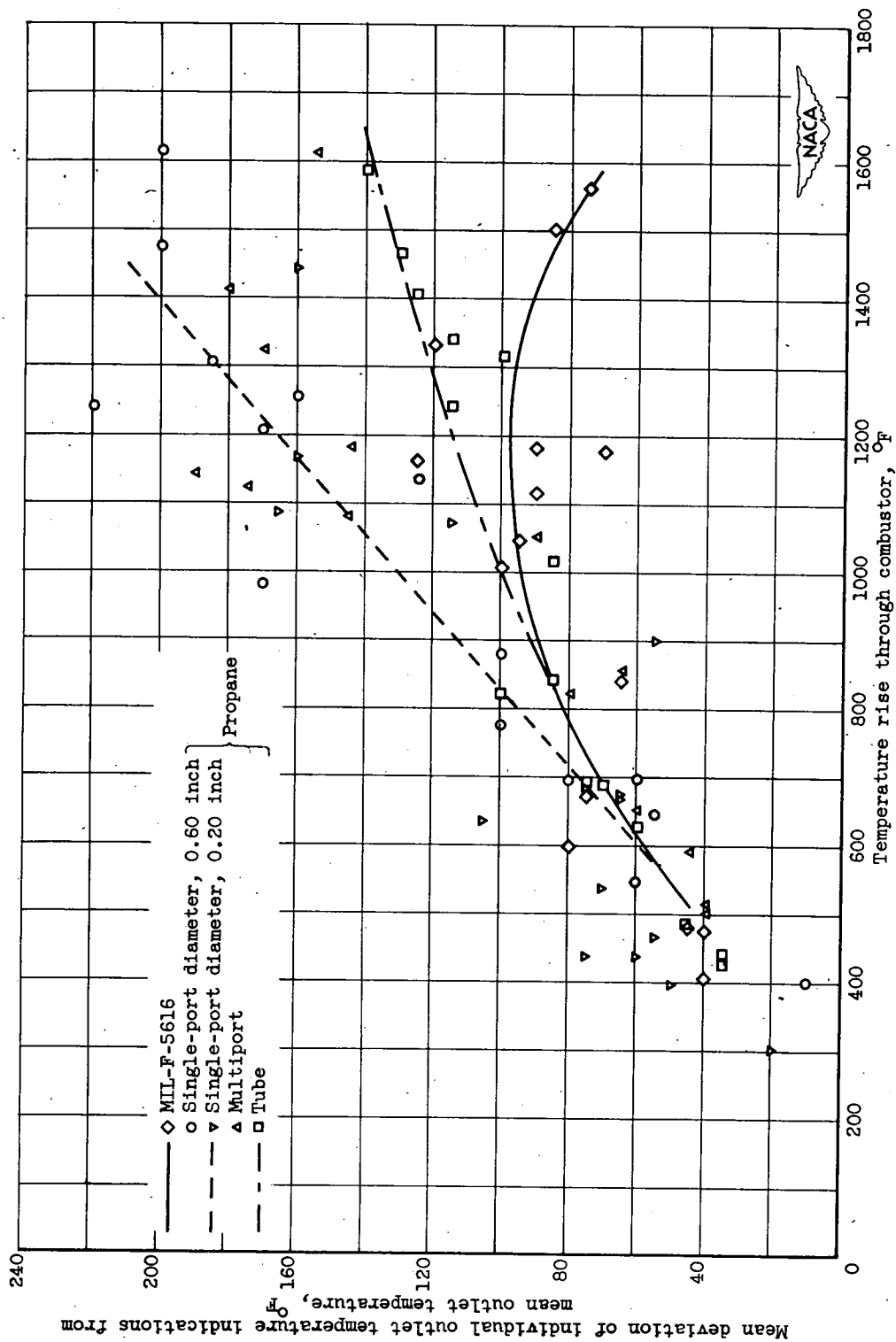


Figure 12. - Variation of mean deviation of individual outlet temperature indications with temperature rise through tubular combustor operating with liquid and vapor hydrocarbon fuels injected by several different methods.



Figure 13. - Multiport propane injector showing carbon deposits formed during investigation.